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Behavior of R.C. Beams with Openings using Different Strengthening Techniques

Alaa M. Morsy[a*], Amr M. Barima[b]

[a]*Ass.Prof. College of Engineering & Technology, Arab Academy for Science, Technology and Maritime Transport*

[b]*B.Sc. MSc student. College of Engineering & Technology, Arab Academy-y for Science, Technology and Maritime Transport*

[a]*Email: alaamorsy@aast.edu*

[b]*Email: amrbarrima@gmail.com*

Abstract

An extensive experimental program was performed to investigate the performance of R.C. beams with opening either strengthened or un- strengthened. A total of 24 specimens were tested on two series to examine the effect of openings on the behavior of RC beams according to the opening shape, aspect ratio and orientation having same area of the opening in shear and flexural zones, also study the effect of the different strengthening methods for the openings on the behavior of RC beams either using internal strengthening such as internal steel reinforcement (I.S.R.), internally embedded fiber reinforced bars, and near surface mounted using FRP laminate (N.S.M.) or using external bonding strengthening (E.B.) such as externally bonded FRP laminates and steel box. All specimens tested under three points loading, the effective span of beams was 1500 mm, also all specimens designed to govern failure in flexure before shear. Based on the experimental evidence, in the 1st series circular openings showed the least reduction in the beam's load capacity when compared to rectangular and square openings regarding all the openings shapes have the same area. The 2nd series showed the effect of strengthening the openings on the behavior of beams, the use of CFRP externally bonded improves both beam's strength and ductility but to different extents than any different method of strengthening.

Keywords: Opening; Shear; Flexural; Strengthening; FRP; NSM; ductility.

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* Corresponding author.

1. Introduction

Reinforced concrete structures sometimes face modification during their service life, making web openings in reinforced concrete R.C. beams is frequently required to accommodate essential services such as air conditioning conduits, water supply, electricity, and heating ducts. The transverse openings in beams are a source of potential weakness. The creation of such openings in existing RC beams produces discontinuity in the normal flow of stresses which would reduce the beam shear capacity and stiffness and leading to early cracking of concrete [1]. Many researchers study the effect of drilling an opening through the beam web and the deterioration found in the shear capacity which depend on the position of the opening either passes through the path between the load and support which increase the reduction of the beam load capacity or in other position [2-5]. Similarly the effect of drilling open at the flexural zone in the entire span or an opening in each half-span continuous rectangular RC beams with a large rectangular opening indicated that the collapse load decreases and the deformations increase as the opening is located at a higher moment region of the beam. The cracking and collapse loads decreased and the vierendeel action became more pronounced with increasing opening dimensions. Also they have developed a method for calculating the deflections of RC beams with a large rectangular opening by assuming that a contra flexure point forms at mid-length of each chord in vierendeel mechanism. This method considers a beam with opening as a non- prismatic one, where sections with opening have reduced shear and flexural rigidities [5-9]. In order to prevent this reduction of shear and flexural capacity special reinforcement enclosing the opening should be provided in the form of external or internal reinforcement. Internal reinforcements are steel bars provided along the opening with the main reinforcement prior casting, or by embedding internally reinforcing bars inside the structure which known by internally embedded reinforcement (I.E.R.) [10]. The effectiveness of externally bonded CFRP composite system to increase the shear capacity of solid RC beams (i.e., without web openings) has been reported in the literature by many researchers [11-14]. FRP composite materials are an excellent option for external reinforcement because of their superior properties as high specific stiffness and specific strength, ease of installation, possibility of application without disturbing the existing functionality of the structure, non-corrosive and nonmagnetic nature of the materials along with its resistance to chemicals. It has been widely shown that to increase the shear capacity and ductility of RC beams with web openings, it is necessary to increase the amount of the internal web reinforcement around the openings. External reinforcements are applied externally around opening in the form of jacketing of steel plates or composite materials like glass fiber or carbon fiber reinforced polymer called GFRP or CFRP. FRP composite materials can be used in strengthening by either externally bonding the laminates or the sheets with an adhesive material, or by internally by making groves near the surface which is known by near surface mounted technique [15-21].

2. Research Scope and Objective

The comprehensive experimental investigation was divided into two main parts; first part was undertaken to study the behavior of R.C. beams with openings with different shapes, aspect ratio and orientation in different locations for flexural and shear zone failure, the main objective of this part is two examine the effect of those parameters on the load capacity, crack pattern and deflection of those beams and the optimum shape, size and orientation in the case of making opening in the beam in flexural or shear zone. In addition the second part of this investigation to study the different techniques of strengthening were used to strengthen the square openings in flexure and shear zones using two main techniques; first method was internally before casting concrete like adding extra steel reinforcement around the opening or after casting like internally embedded reinforcement (I.E.R.) either using steel or FRP, near surface mounted (N.S.M.), and FRP laminate, second method was externally using external bonding FRP sheets. Finally, the research could recommend which method of strengthening is optimum in case of flexural and shear.

3. Experimental Program

3.1 Materials and Concrete Mix Proportions

The concrete used in these tests had a strength of 40 MPa based on testing 100 mm cubes, the beams were cured for 28 days. The steel bars used for the flexure reinforcement had nominal yield strength of 360 MPa, modulus of elasticity 200 MPa and tensile strength 520 MPa while the bars used for Stirrups had nominal yield strength of 240 MPa. The materials used during strengthening process, Sika Carbodur rods with diameter 12 mm used for internally imbedded reinforcement method for strengthening, the rods tensile strength is 2800 MPa, modulus of elasticity 155 GPa and ultimate strain 1.8%. While CFRP laminates with thickness 1.2 mm, Elasticity modules 165 GPa, and tensile strength 2800 MPa were used as near surface mounted technique with Sikadur -30LP epoxy adhesive was used as bonding agent.

3.2 Description of beams

The specimens were divided into two groups with total of 24 half scale beams, of total length 1700 mm and effective span 1500 mm, the cross section area width 120 mm and height 300 mm ; the first series study effect of openings in beams in different zones. In the first series the opening shape, and orientation was the main parameter, square, rectangular and circular openings were studied. The area of the openings was the constant in all the shapes -of about 144 mm^2, the square opening was 120 X 120 mm, the rectangular openings were 98 X 147 mm with aspect ratio 1.5 and 85 X 170 mm with aspect ratio 2.0 while the circular opening had 135 mm diameter. The rectangular openings with aspect ratio 2.0 studied the orientation of the opening whether the opening was horizontal or vertical, as well as the tilted square “rhombus”.

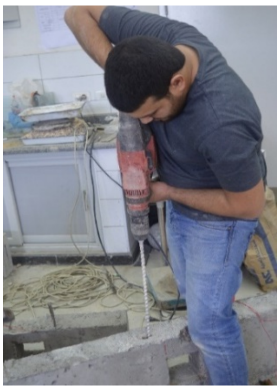

Figure 1: Drilling I.E. R technique

Figure 2: Embedding N.S.M technique

The second series which study the effect of strengthening, all openings were square shape with different techniques in different failure zones, Figure (1) shows the drilling of hole along the beam height around the opening vertically for embedding the FRP reinforcement, while Figure (2) shows the groove which has been cut for embedding the FRP laminate above and below the opening. The whole flow chart for the examined parameters showed in Figure (3), include the two series of the experimental program either in flexural failure zone or shear failure zone

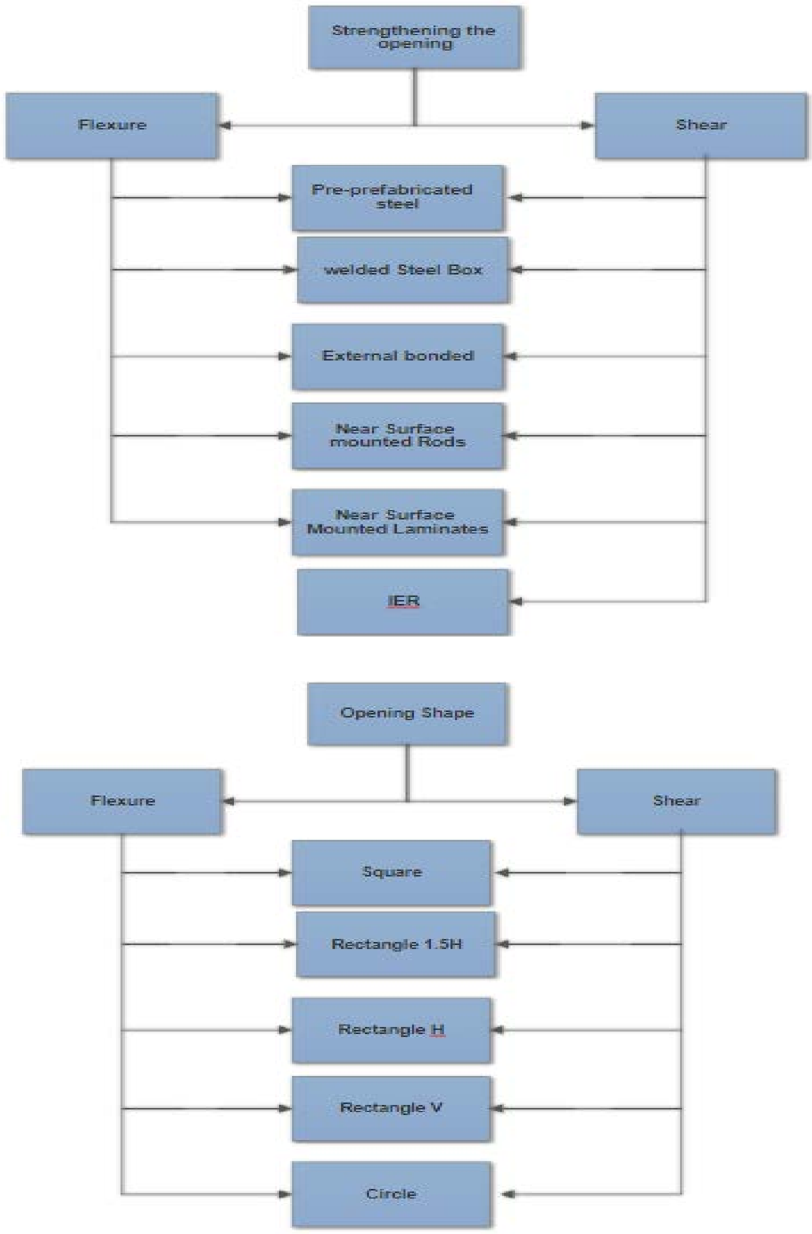

Figure 3: Flow chart for the tested beams parameters

Table 1: The Studied Parameters

No.		***Col Code***	***Opening Size (mm)***	***Strengthing Tecnique***	***Strengthing Material***	***Dimmensions of Strengthing Material (mm)***
1	Un- strenghned	Control	None	None	None	None
2		F-S	120 X 120	None	None	None
3		F-R-1.5H	98X147	None	None	None
4		F-R-2V	85X170	None	None	None
5		F-R-2H	85X170	None	None	None
6		F-S-45º	120X120	None	None	None
7		F-C	R67.5	None	None	None
8		S-S	120 X 120	None	None	None
9		S-R-1.5H	98X147	None	None	None
10		S-R-2V	85X170	None	None	None
11		S-R-2H	85X170	None	None	None
12		S-S-45º	120X120	None	None	None
13		S-C	R67.5	None	None	None
14	Strengthened	F-R	120 X 120	Internal Steel Rods during casting	Steel rods	12 mm bars
15		F-L-N	120 X 120	Near Surface Mounted Lamintes	CFRP Lamintes	24 mm width
16		F-L-E	120 X 120	Exteral Lamintes	CFRP Lamintes	48 mm width
17		F-L-Steel	120 X 120	Steel Box inside the opening	Steel Lamintes	8 mm Lamintes
18		F-R-N	120 X 120	Near Surface Mounted Rods	CFRP Rods	12 mm bars
19		S-R	120 X 120	Internal Steel Rods during casting	Steel Rods	12 mm bars
20		S-LSteel	120 X 120	Steel Box inside the opening	Steel Lamintes	8 mm Lamintes
21		S-L-N	120 X 120	Near Surface Mounted Lamintes	CFRP Lamintes	24 mm width
22		S-R-N	120 X 120	Near Surface Mounted Rods	CFRP Rods	12 mm bars
23		S-R-IER	120 X 120	Internally embedded reinforcement	CFRP Rods	12 mm bars
24		S-LE	120 X 120	External Lamintes	CFRP Lamintes	48 mm width

Abridgment of words had been used to make it easy to recognize the description of each beam, so the 1st alphabetic letter “F” refer to the beam with opening in flexure zone; and "S” refer to the type of opening in shear zone. The 2nd alphabetic letter "S” refer to the square openings, “R” will refer to the rectangular opening and “C” will refer to the circular opening. The 3rd combination of letters refer to the technique of strengthening used for each specimen “R” will refer to the internal extra reinforcement around the opening, “SB” refer to a steel box made of welded steel laminates, “NL” will refer to near surface mounted FRP laminates. “NR” will refer to near surface mounted FRP rods, and “LE” will refer to externally bonded FRP laminates. Also, another technique was used for strengthening in shear zone only by imbedding FRP rods vertically along the beam height referred to it by I.E.R. The summary of beams nomination, openings size, shape, strengthening technique and the material used in strengthening for both flexural and shear failure zone shown in Table (1)

3.3 Test Setup and preparations

Before casting the specimens, strain gauges were installed to measure the strain in both longitudinal bars and stirrups. The strain gauges were applied at the mid span of the beam on the longitudinal reinforcement and in the shear zone on the stirrups. Also, another strain gauge was applied to the FRP laminate or rods in the strengthened beams. A total of 24 beams were tested under 3 points loading. A deflection control mode was performed throughout the experimental program. The spacing between stirrups was 75 mm with 8 mm diameter and the lower and upper reinforcement as 2 bars of 12 mm diameter this configuration governs the failure to occur in flexural zone. Figure (4) shows the beam test setup and the steel reinforcement configuration.

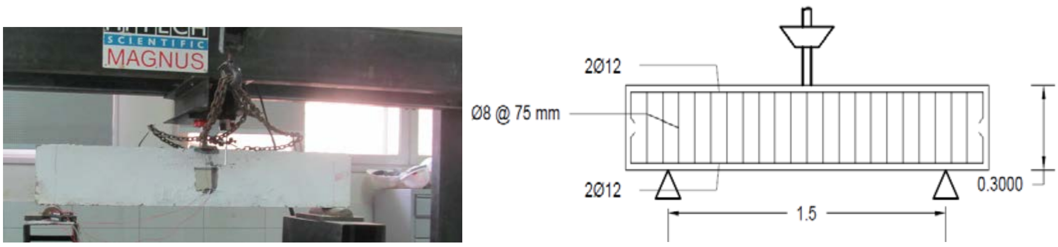

Figure 4: The beam test setup and the steel reinforcement configuration

4. Test Results and Analysis

4.1 Crack pattern & Mode of failure

Most of the failure modes of all beams divided mainly into two failure modes, 1st failure mode represents the un-strengthened beams failure where the opening was made in the web of the beam and no strengthening was implemented, the failure mode of the beam changed to brittle shear failure as shown in Figure 5 and Figure 6. In these beams, large diagonal cracks formed near the corner of the opening and extended to the point of the applied load and to the support, bringing about an abrupt failure. The beam with square opening tended to have a lower capacity than that with circular opening even though the failure mechanism was the same as shown in Figs 6 and 8 for flexure zone and Figs 9 and 10 for shear zone. This behavior is due to the formation of early diagonal cracks around the corner of the opening due to the stress concentration.

The 2nd failure mode represent the strengthened beams, beams F-L-N and S-L-N which strengthened in flexural and shear using FRP laminate as near surface mounted, crack pattern was similar to the control beam, however in beam S-L-N more diagonal cracks appeared in the un-strengthened zone. Beams -L-E and S-L-E experienced a failure due to the de-bonding of laminates from the concrete cover leading to a brittle failure. This presence of FRP laminates tend to interrupt the natural path of crack propagation, thus once the bond between the FRP and concrete fails it cause a sudden change in the flow of the energy and the crack path to the weak zone leading to a sudden and brittle failure. Here below detailed explanation of the failure mode and crack pattern of all tested beams

Control Beam

The first crack was observed at load of 3.0 ton in the flexure zone. No sign of action was observed in the shear zone till load of 7.0 ton according to the steel configuration designed prior to casting to govern the failure in flexural zone. (i.e., the flexural capacity was designed to exceed the shear capacity of the tested beams. At load of 9.0 ton a crack was noticed in the compression zone, the failure happened at a load of 11.0 ton in flexure zone followed by failure in compression. As shown in Figure 5.

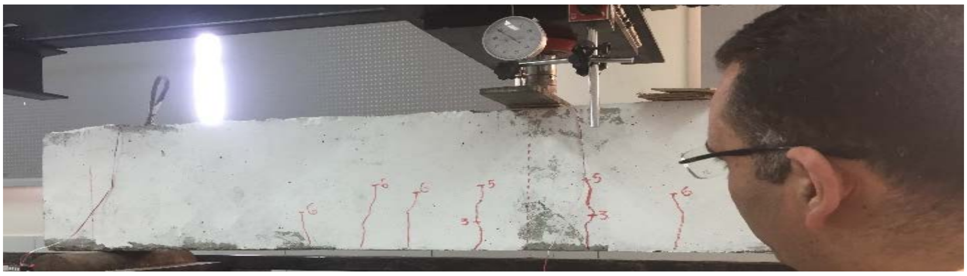

Figure 5: Control beam

The two main failure modes for strengthened and un-strengthened beams have been explained in the following session either for flexural or shear zone failure

Failure mode 1 (A) flexural zone failure "un- strengthened beams with opening"

Beam F-S

Beam F-S is a control beam with a square opening in the flexure zone with no strengthening, the first crack was in flexure zone at load of 3.0 ton at the bottom of the opening, the cracks kept spreading and forming new cracks till the load of 9.0 ton, at load of 9.2 ton a severe complete failure in the concrete cover accompanied with crushing of compression zone and this failure may be called flexural compression failure followed by spalling of side part of concrete cover, showing a 16% reduction in the load capacity compared with the control beam as shown in Figure 6.

Figure 6: Crack pattern for beam F-S

Beam F-R-2V

Beam F-R-2V is a control beam with a vertical rectangular opening with aspect ratio 2 in the flexure zone with no strengthening. The cracks were observed at load 4.0 ton, new cracks were observed in the compression zone at load 7.0 ton, the failure happened in the compression zone followed by failure in flexure zone at load 9.0 ton showing a 16% reduction in the load capacity compared with the control beam, as shown in Figure 7.

Figure 7: Crack pattern for beam F-R-2V

Beams, F-R-2H, F-S-45 and F-R-1.5H

All those beams have the same behavior, the first crack was observed at load 3.0 ton at the flexure zone, at load of 6.0 ton new diagonal cracks were observed from the bottom lower corner of the opening to the mid span of the beam. The failure happened in the Flexure zone at almost the same load 9.0 ton followed by failure in the

Figure 8: Crack pattern for beam F-R-1.5H

compression showing reduction 18.2% in load capacity compared with the control beam as shown in Figure 8.

Beam F-C

Beam F-C is a control beam with a circular opening in the flexure zone with no strengthening. The first crack was observed at load 3.0 ton, all cracks were observed at the flexure zone, the failure happened at load 10.0 ton in the flexure zone with a reduction 10% only as shown in Figure 9, the delay of the failure was due to the absence of the diagonal cracks that happens due to the stress concentration on the opening corner.

Figure 9: Crack pattern for beam F-C

Failure mode 1 (B) Shear zone failure "un- strengthened beams with opening"

Beams S-S and S-S-45

Beams with square opening with different angles, the First crack s and kept increasing starting from 4.0 ton where a crack happened in the flexure zone, Also a diagonal crack around the opening appeared in the shear zone and kept increasing. At load of 7.0 ton the failure happened in the shear zone with 36.4% reduction in the load capacity compared with control beam as shown in Figure 10.

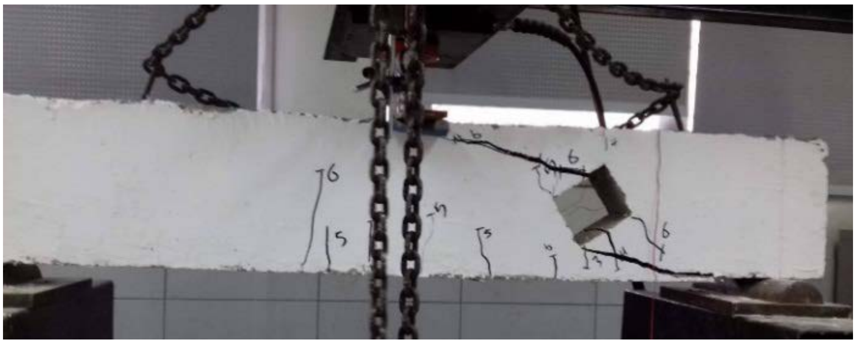

Figure 10: Crack pattern for beam S-S-45

Beams S-R-1.5H, S-R-2H   and Beam S-R-2V

The three beams had a rectangular opening with different aspect ratio and orientation. The mechanism of failure was the same in the beams, the first crack happened at 3.0 ton from the corner of the opening and extend toward the support and the point of loading, new cracks in flexure zone was observed at 5.0, and increased at 7.0 ton Then the failure happened in shear zone at load of 8.0 ton, 7.2 ton and 6.2 ton respectively due the formation and spreading of the early diagonal cracks as shown in Figure 11.

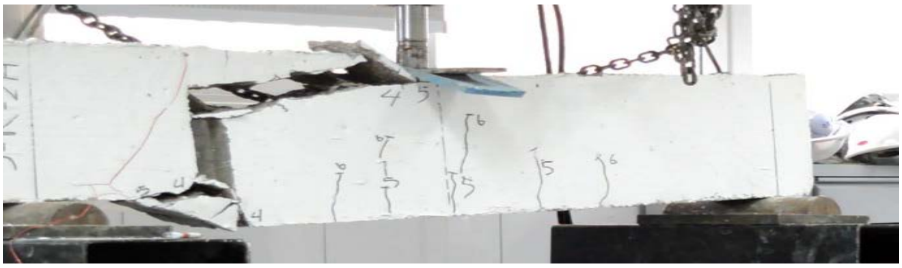

Figure 11: Crack pattern for beam S-R-2V

Beam S-C

The 1st crack was observed at load 3.0 ton in the flexure zone, at load 6.0 ton new crack appeared in the shear zone, new diagonal cracks kept appearing till the failure at load 9.5 ton in the shear zone as shown in Figure 12 with reduction 13.6% in load capacity compared with the control beam.

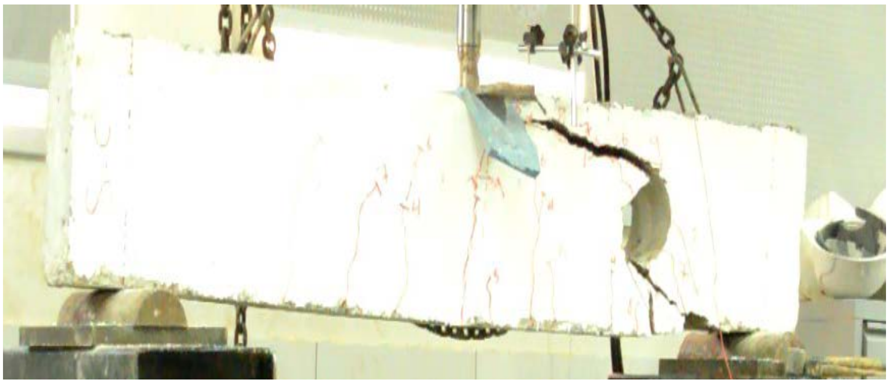

Figure 12: crack pattern for beam S-C

Failure mode 2 "Strengthened beams" in flexural and shear zone

Beam F-R, Beam S-R

Both beams have strengthened using internal square steel reinforcement around the opening prior casting. The first crack was observed at load of 4.0 ton, at load 7.0 ton crack appeared in the shear zone of beam S-R in the un-strengthened part. The failure of the beams was in Flexure zone with load of 9.2 ton showing enhancement in the load capacity by 8.23% and 31.42% for flexure zone and shear zone compared by beams F-S and S-S respectively, several diagonal cracks were observed extremely before the failure of the beam. In spite of the reduction in load capacity due to opening in shear zone was much higher than flexural zone; the effect of strengthening in the shear zone shows more efficiency than flexural zone, as shown in Figure 13 and 14. Reinforcing the beam internally around the opening showed a success in enhancing the performance of the beam, however it may not be able to use this technique if the opening was made after casting the beam, so other techniques should be used in case of strengthening only.

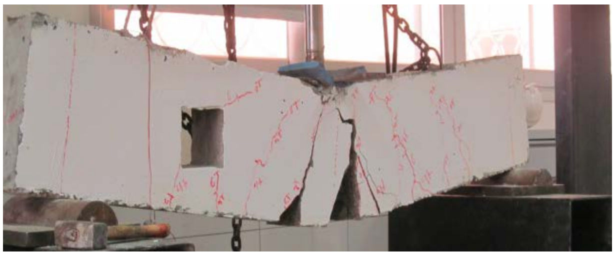

Figure 13: Crack pattern for Beam S-R

Figure 14: Crack pattern for beam F-R

Beam S-L-Steel

This beam strengthened by embedding a square steel box of thickness 8 mm. The first crack appeared in the flexure zone at load 4 ton, also at 4 ton diagonal crack appeared in the shear zone around the opening, new diagonal cracks appeared at load 5 and 6 ton around the opening, and increased at load 7 ton. The failure happened in the shear zone at load 8.5 ton due to the diagonal cracks damaging the welding of the steel box as shown in Figure 15 showing a 21.4% enhancement in the load capacity compared with beam S-S. Using a steel box didn’t show a successful result in strengthening the opening in the shear zone, because the shear force tends to break the welding of the steel plates forming the box so it becomes ineffective.

Figure 15: crack pattern for beam S-L-Steel

Beam F-L-N

The first crack appeared at load 3 ton in the flexure zone, the diagonal crack started to appear at load 5 ton around the opening at increased at load 7 ton. At load 5 ton Flexure-shear cracks appeared and increased at load 7. At load 9 ton a new crack appeared in the flexure zone and compression zone followed by Failure at load 9.3 ton showing 15.4% enhancement in load capacity compared with beam F-S, the failure happened due to the de-bonding of the FRP laminates from the grove as shown in Figure 13. Separation of FRP laminates from the groove was noticed in failure, but there was no deboning in the bond between the RC and FRP which shows that the epoxy bonding the RC and FRP was stronger than the bond between the concrete itself. As shown in Figure 16.

Figure 16: Crack pattern for beam F-L-N

Beam S-L-N

The first crack was observed at load of 3.0 ton in the flexure zone, and kept increasing at load of 4.0 and 6.0 ton, at load of 7.0 ton new crack appeared in the flexure zone and kept increasing till 10.0 ton toward the loading point. The first crack in the shear zone appeared at load 8 ton showing the strengthening made a great improvement to prevent the failure in the shear zone. The failure happened at load 10.1 ton in flexure zone and no deboning in the FRP was observed as shown in Figure 17. Showing the highest enhancement in load capacity compared with beam S-S with 44.2%.

Figure 17: Crack pattern for beam S-L-N

Beams F-RN and S-RN

The first crack was observed 4.0 ton around the openings and increased at load 9.0 ton in the flexure zone, new cracks appeared in flexure at load 5.0 and 6.0 ton and increased at load 8.0 and 9.0 ton.

The failure occur in the flexure zone at load 9.5 ton for both beams showing an increase in the load capacity by 12% for flexure zone and 35.7% for shear zone compared with beams F-S and S-S respectively as shown in Figs 18 and 19. Which confirm that the results are consistence and the effect of strengthening in the shear zone more effective than flexural zone.

Figure 18: Crack pattern for beam F-R-N

Figure 19: *Crack pattern for beam S-R-N*

Beam F-L-E

The first crack was noticed around the opening at the load of 3.0 ton, at load of 5.0 ton a diagonal crack appeared in the flexure zone and kept spreading from the support toward the mid span, at the load of 9.0 ton separation of the laminate was noticed. Failure happened at load of 9.2 ton as shown in Figure 20. Showing an 8.2% enhancement in load capacity compared with beam F-S. The failure was due to the separation of laminates, shows that the bond between laminates and concrete was stronger than the bond between the

Concrete itself.

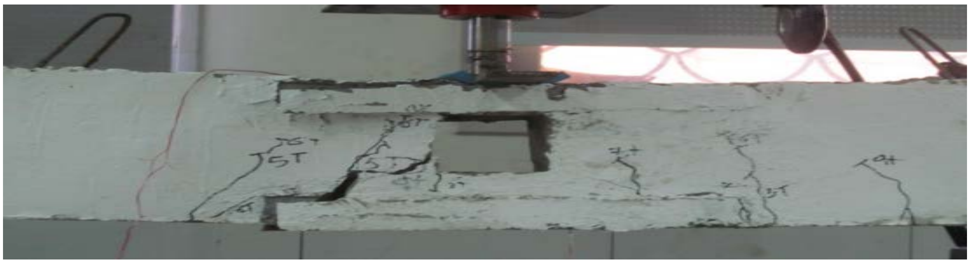

Figure 20: Crack pattern for beam F-L-E

Beam S-L-E

The first crack appeared in the flexure zone at load 3.0 ton and increased at load 4.0 ton, new crack appeared at load 4 ton in the flexure zone and around the opening and increased at load 7 ton, at load 7.0 ton four new cracks was observed in the flexure zone, shear zone and around the opening forming diagonal cracks. The failure happened in the shear zone at load 8 ton showing 15% enhancement in load capacity compared with beam S-S, due to the deboning between the FRP and concrete cover as shown in Figure 21.

Figure 21: Beam S-L-E Crack pattern

Beam S-R-IER

At load 3 ton the 3 cracks appeared in flexure zone and a diagonal crack appeared around the opening, at load 4 and 5 ton new cracks appeared in the flexure and shear zone around the opening. The failure happened in the shear zone at load 7 ton.

Figure 52

Crack pattern for beam S-R-IER

Table 2 shows the summary of all beams first crack, yield and failure load, in addition to the corresponding deflection at those load steps, also the percentage of load reduction than the beams without opening and the percentage of increasing due to strengthening compared to the corresponding strengthened beams with opening.

Table 2: Summary of beam test results

Beam	**Ultimate Load (ton)**	**Load at yield (ton)**	**Δ corresponding to crack load (mm)**	**Δ corresponding to crack load (mm)**	**Δ corresponding to Yield load (mm)**	**% of Decrease due to opening**	**% of increasing due to strengthening**
Control	11	8.1	5.26	18.7	13.83	-	-
F-S	8.5	8.1	8.25	27.1	16.2	22.7%	-
F-R-1.5H	9.0	8.1	6.56	19.76	13.15	18.18%	-
F-R-2V	9.0	N.O.	11.55	19.3	N.O.	16.3%	-
F-R-2H	8.7	N.O.	10.1	18.3	N.O.	20.9%	-
F-S-45	9.0	8.1	6.38	35.5	16.26	18.18%	-
F-C	10.0	8.5	6.2	36.94	31.72	9.09%	-
S-S	7.0	N.O.	11	16.95	N.O.	36.36%	-
S-R-1.5H	8.0	N.O.	6.66	16.7	N.O.	27.2%	-
S-R-2V	7.2	N.O.	6.7	19.55	N.O.	34.54%	-
S-R-2H	6.2	N.O.	12.7	19.5	N.O.	43.63%	-
S-S-45	7.0	N.O.	15.99	21.9	N.O.	36.36%	-
S-C	9.5	N.O.	6.19	26.3	N.O.	13.6%	-
F-R	9.2	N.O.	10.7	22.5	N.O.	16.3%	8.23%
S-R	9.2	N.O.	8.77	31.77	N.O.	16.3%	31.42%
F-L-Steel	9.2	N.O.	2.44	35.8	N.O.	16.3%	8.23%
S-L-Steel	8.5	N.O.	12.56	28.32	N.O.	22.7%	21.42%
F-R-N	9.5	N.O.	5.1	14.99	N.O.	13.6%	11.76%
S-R-N	9.5	N.O.	8.52	18.52	N.O.	13.6%	35.7%
F-L-N	9.3	N.O.	13.1	34.55	N.O.	15.4%	16.25%
S-L-N	10.1	N.O.	7.5	34	N.O.	8.18%	44.2%
F-L-E	9.0	N.O.	10.05	17.68	N.O.	18.18%	5.88%
S-L-E	8.0	N.O.	9.3	23.3	N.O.	27.2%	14.2%
S-R-IER	7.0	N.O.	6.85	30.65	N.O.	36.36%	0%
N.O. Not Occur, showing that no yielding happened in the refereed beam							

5. Parametric Study Analysis

5.1 Effect of the opening shape in shear and flexural zone

Generally creating an opening in the beam greatly decreased the load capacity of the beam especially when the opening in the shear zone rather than flexural zone which proved by this experimental results. The circular opening showed the highest performance compared with the other opening shapes in both shear and flexure zones with the lowest reduction compared to beam without opening of 13.6% and 9.1% respectively as shown in Figure 21 & 22 compared with the control beam. Due to absence any stress concentration on the circular opening as there is no edges in the circular shape, this tends to distribute the load efficiently on the surface of the opening which delays the failure.

The horizontal rectangular opening with aspect ratio 1.5 showed a better performance than the square openings showing an increase in the load capacity 14.2% and 5.8% in shear and flexural zones respectively over the square opening, in addition that the reduction in load capacity compared to the beams without opening reach 27.2 % and 18.2 % for shear and flexural zones respectively.

The square opening showed reduction 36.4% and 22.7% in the load capacity in shear and flexure zones respectively over the control specimen. Also the reduction in shear zone much greater than flexural zone, so it is highly recommend to make open in flexural zone rather than shear zone if needed to make open urgently. Also it is not recommended to make the shape of opening square and making it circular or rectangle much better than square having the same cross section area.

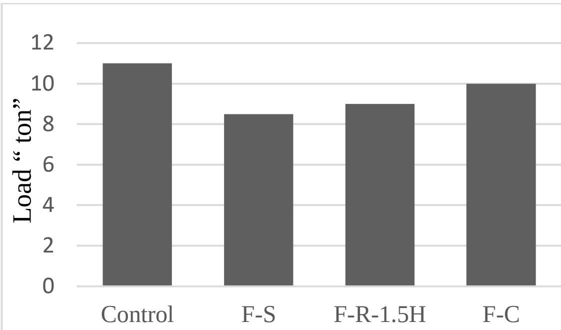

Figure 21: Load Capacity for beams with opening in flexure zone

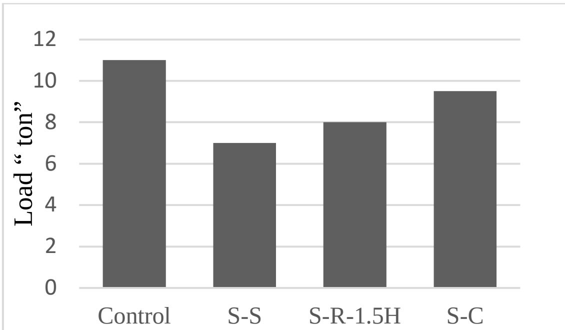

Figure 22: Capacity for beams with opening in shear zone

5.2 Effect of orientation of the opening in shear and flexural zone

Overall changing the orientation of square opening either 90^o or 45^o "Rhombus" did not make any significant change either in shear and flexural zone as shown in Figure (23) and (24), on the other hand

changing the orientation of the rectangular opening with aspect ratio 2.0 from vertical to horizontal could make effect as the vertical opening have lower reduction in the load capacity over the control beam in both shear and flexural zone, and the increase in the ultimate capacity in case of vertical opening over horizontal opening reach

16% in shear zone and 5% in flexural zone. Accordingly, it is recommended to make the rectangular opening in vertical position rather than horizontal

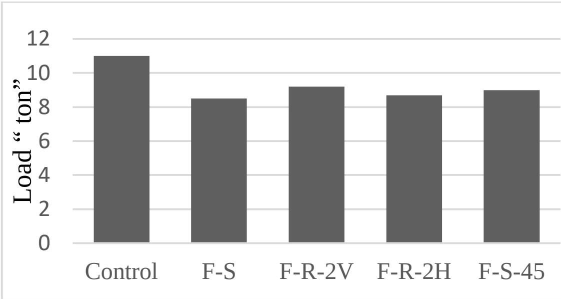

Figure 23: Load capacity with openings in shear zone

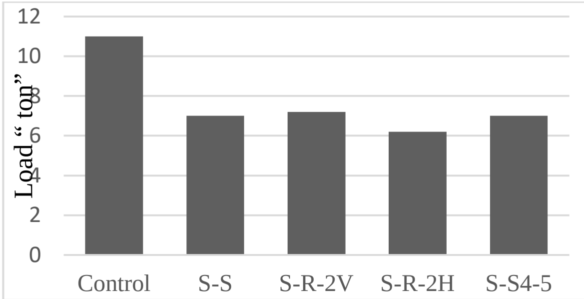

Figure 24: Load capacity with openings in the flexure zone

5.3 Effect of Aspect ratio of the opening in shear and flexural zone

By keeping the area of the opening a constant, we could change the aspect ratio of the square opening to give two more different horizontal rectangular shapes with aspect ratio 1.5 and 2.0, as shown in Figure 25 &26 changing the aspect ratio in flexure zone showed a slight decrease between aspect ratio 1.5 and 2.0. On the other hand the change in aspect ratio has more influence in shear zone opening between rectangular shapes with aspect ratio 1.5 and 2.0 with 27.2% reduction only for aspect ratio 1.5 compared to 43.6% for aspect ratio 2.0

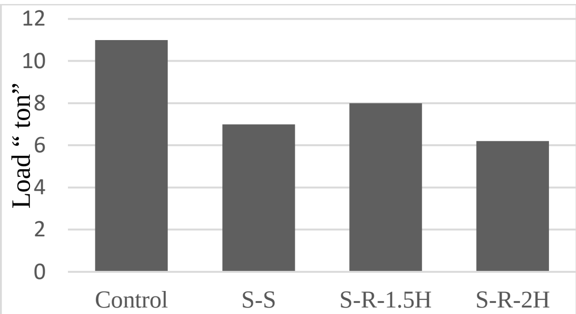

Figure 25: load capacity for beams with opening in flexure zone

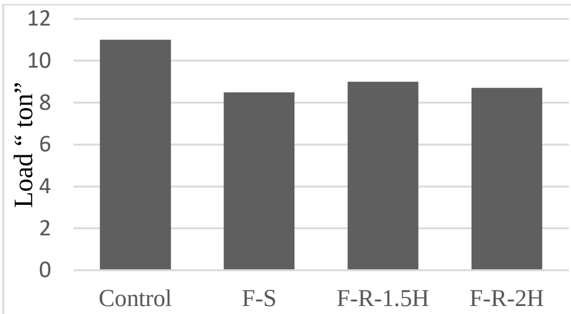

Figure 26: load capacity for beams with opening in shear zone

5.4 Effect of External methods of strengthening in shear and flexural zone

5.4.1 Effect of external FRP laminates

Figs 27 and 28 shows the capacity of beams strengthened with externally bonded laminates, it shows that externally bonded laminates enhanced the load capacity of beams with openings with 8.2% for the opening in flexure zone and 14% for the opening in shear zone. For Beam S-L-E despite strengthening the beam the mechanism of failure didn't change compared with Beam S-S which didn't have any strengthening, showing that the EB strengthening technique was not very effective in the shear zone.

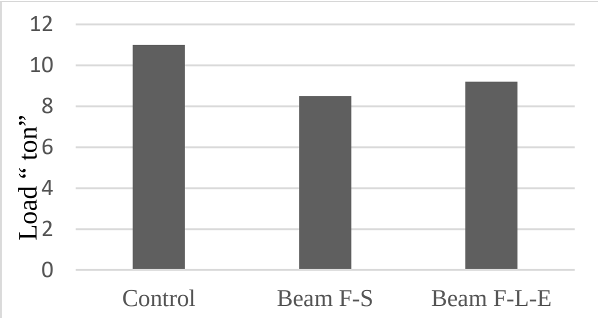

Figure 27: load capacity for beams strengthened with FRP laminates in flexure zone

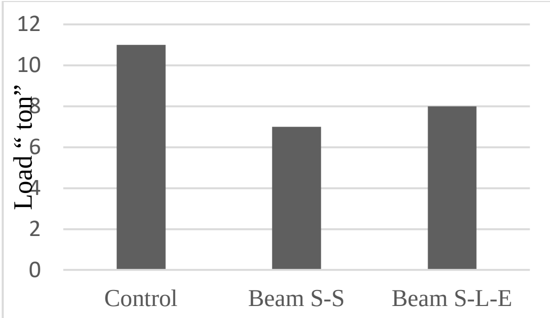

Figure 28: load capacity for beams strengthened with *FRP laminates in shear zone*

The load deflection curves of beam F-L-E and S-L-E shown in Fig 29 and 30 shows that the FRP laminates increased the stiffness of the beams compared with beams F-S and S-S, beam F-S is tougher than beam F-L-E showing that the failure happened due to the early diagonal cracks in beam F-S, Also the laminates delayed the failure but caused a brittle failure because of the laminates de-bonding.

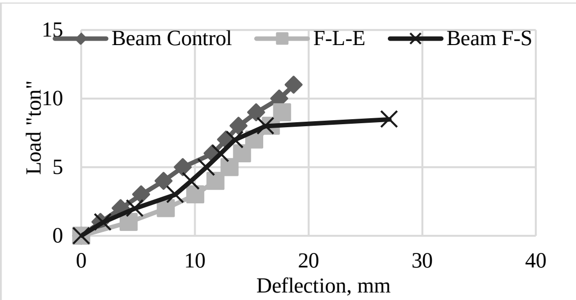

Figure 29: load deflection curve for beam F-L-E

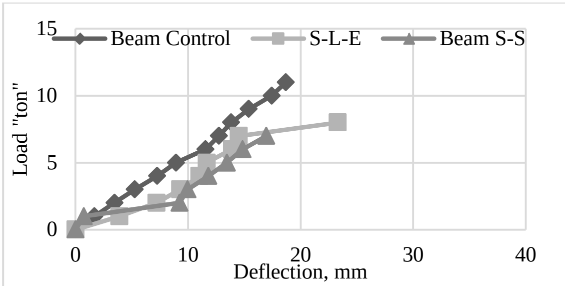

Figure 30: load deflection curve for beam S-L-E

5.4.2 The effect of External Steel box

Strengthening the opening with a steel box was effective for beam F-L-S as the failure load was 9.2 ton showing that the load capacity of the beam is increased by 8.2% compared with beam F-S which didn't have any strengthening. However, for beam S-L-S the failure load was 8 ton with an improvement 14% also the mode of failure didn't change showing that it was not very effective.

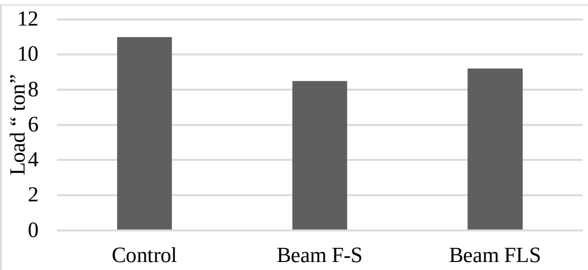

Figure 31: load capacity for strengthened beam with steel box in flexure zone

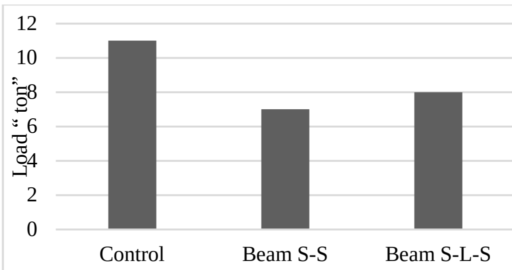

Figure 32: load capacity for strengthened beam with steel box in shear zone

Load-deflection curve of beam F-L-S shows that the deflection of the beam at the first crack of 3 ton was lower than the Control and F-S beam, also shows that the steel box increased the stiffness of the beam compared with beam F-S. However, for beam S-L-S the deflection increased compared with beam SR and beam Control.

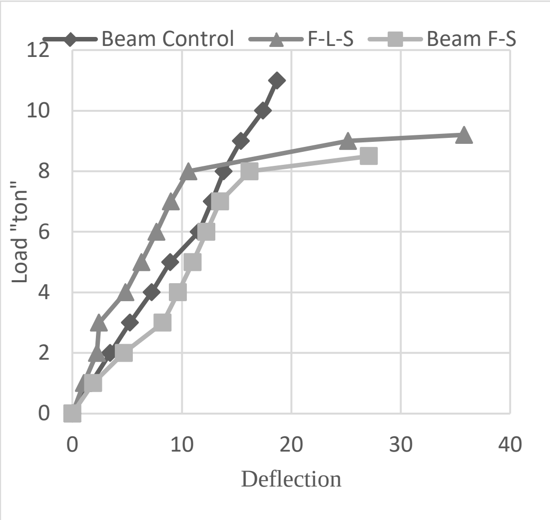

Figure 33: load deflection curve for beam F-L-S

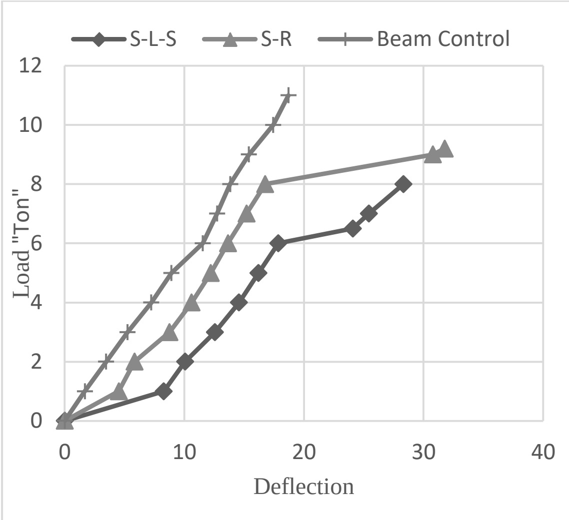

Figure 34: load deflection curve for beam S-L-S

5.5 Effect of internal methods of strengthening in shear and flexural zone

5.5.1 Effect of strengthening internally by prefabricated steel bar

Strengthening the beams internally with steel bars led to increasing the load capacity of the beam compared with the beams without strengthening. Showing that strengthening in shear showed more effectiveness than in flexure. This shows an improvement with 11.7% and 31% for flexure and shear respectively compared with beams F-S and S-S.

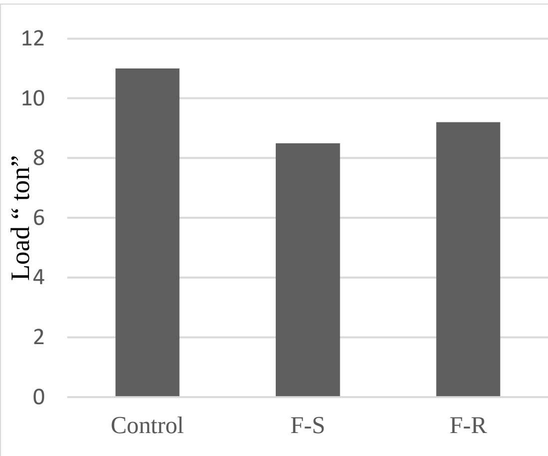

Figure 35: Load capacity chart for beam F-R

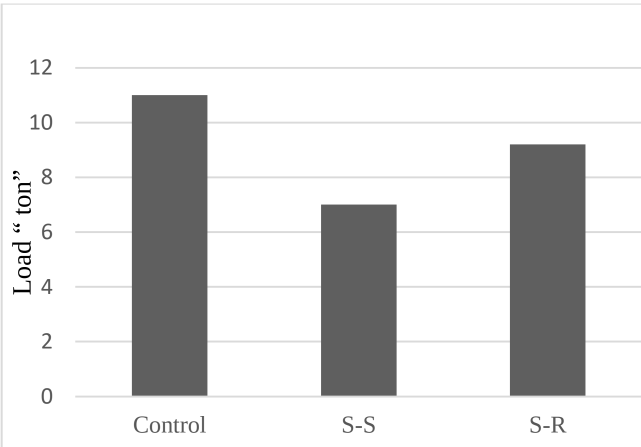

Figure 36: load capacity chart for beam S-R

The load deflection curve of beam S-R shows an enhancement in the toughness of the beam as a result of the internal strengthening with steel before casting as shown in Figure 38.

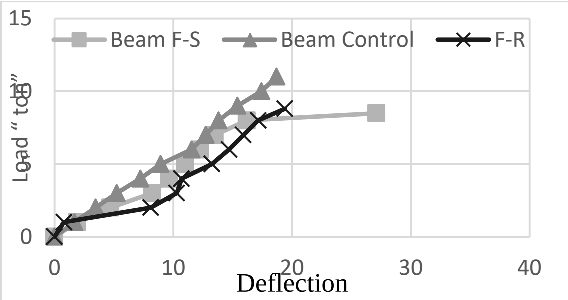

Figure 37: load deflection curve for beam F-R

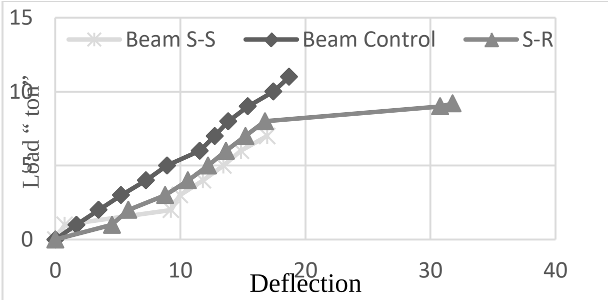

Figure 38: load deflection curve for beam S-R

5.5.2 Effect of near surface mounted rods strengthening

The load chart below shows the effect of strengthening with near surface mounted FRP rods, beams F-R-N and Beam S-R-N load capacity increased compared with beams F-S and S-S.

The chart shows a reduction in the load capacity of 13.6% for Beam F-RN and S-R-N compared with the control beam as shown in Figs 39 and 40.

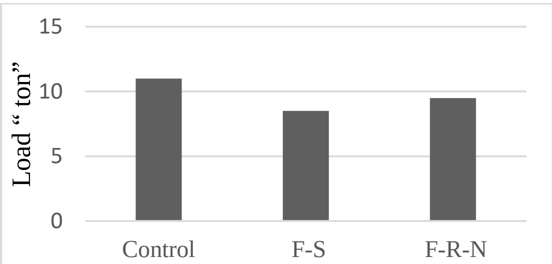

Figure 39: load capacity chart for beam F-R-N

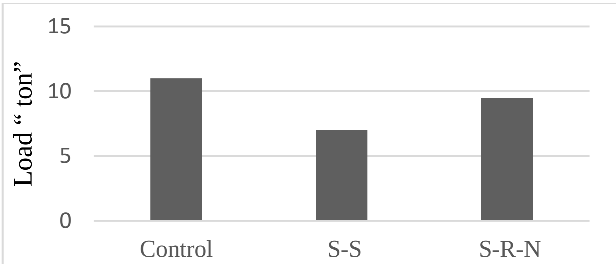

Figure 40: load capacity chart for beam S-R-N

Also, the charts show an enhancement in the load capacity of 11.7% and 35% for beam F-R-N and S-R-N respectably. The load-deflection curve of beam S-R-N shows that the behavior of the beam didn't change compared with the control beam, which Cleary indicted that the beam S-R-N is almost as stiff as beam control. However, beam F-R-N is stiffer than the control beam.

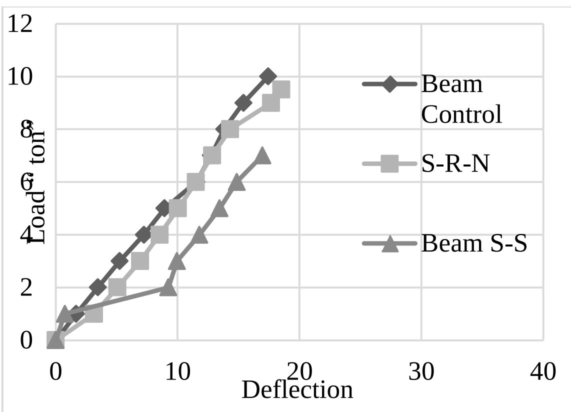

Figure 41: load deflection curve for beam S-R-N

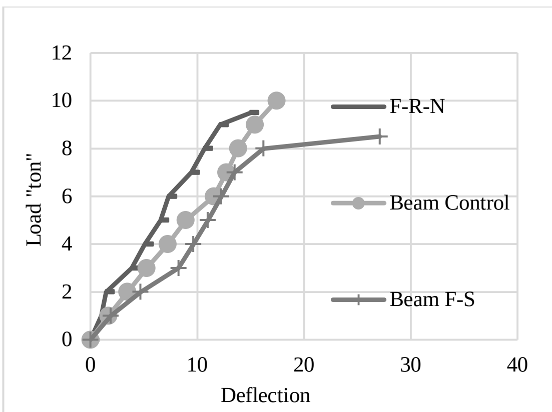

Figure 42: load deflection curve for beam F-R-N

5.5.3 Effect of near surface mounted laminates strengthening

The load chart below shows the effect of using NSM laminates in strengthening the opening in beams. Beam S-L-N failure load was 10.1 ton which shows a significant increase in the load capacity compared with beam S-S which didn't have any strengthening. Also beam F-L-N failure load was 9.3 ton which shows the effect of FRP in strengthening the beam compared with Beam F-S which didn't have any strengthening.

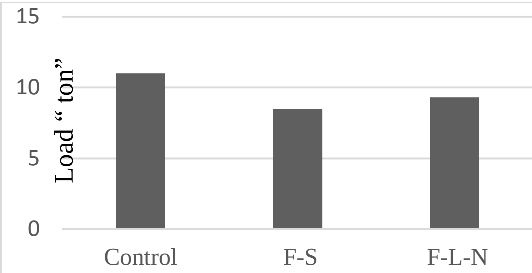

Figure 43: load capacity for beam F-L-N

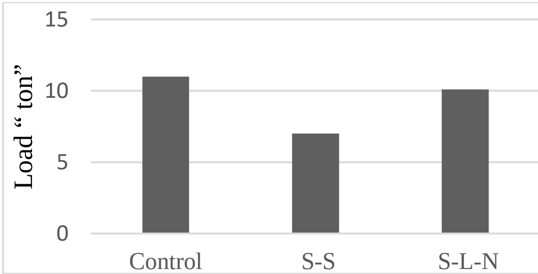

Figure 44: load capacity for beam S-L-N

According to the load-deflection curve above, the stiffness of beam S-L-N increased due to strengthening the beam with FRP laminates compared with beam S-S. Also the toughness of both beams F-L-N and S-L-N enhanced as a result of installing the FRP laminates.

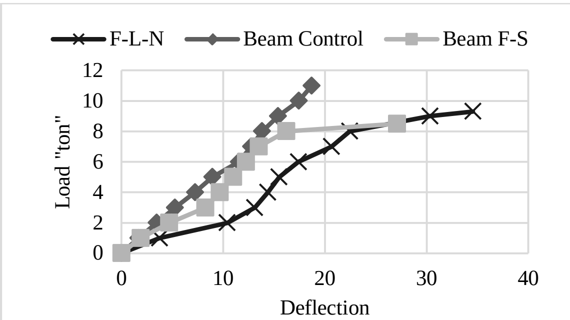

Figure 45: load deflection curve for beam F-L-N

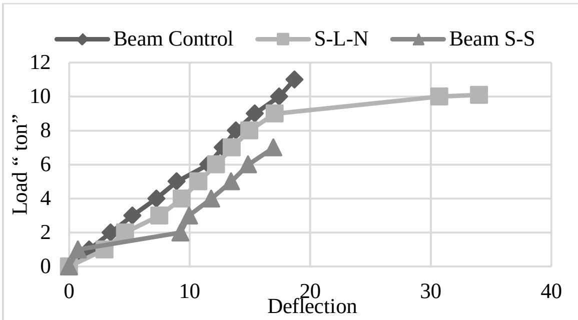

Figure 46: load deflection curve for beam S-L-N

5.5.4 Effect of I.E.R strengthening

Using internally embedded FRP to strengthen the opening in shear zone didn't show any noticeable effect, as shown in Figure (47), showing a conflict with results of the experimental program conducted by Morsy et (2011) using this technique in strengthening R.C. beams in shear without opening [10], the discrepancy in the results may be because opening, or using a driller to make the grooves weakened the beam moreover the weakness caused by the opening. Moreover, the stirrups were used by the minimum spacing which decreased the contact with FRP rods.

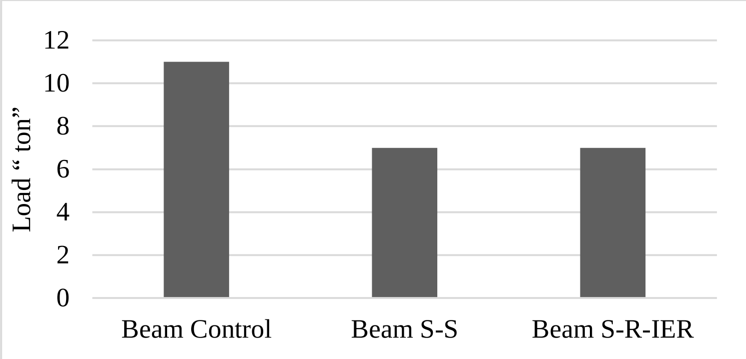

Figure 47: load capacity for beam SR-IER

5.6 Difference between strengthening methods in flexure and shear

The data shown in the previous sections shows the results of strengthening the openings in beams with different techniques, each technique tend to change the behavior and load capacity of the beam with different way whether the opening was in flexure or shear zone. Strengthening the openings internally with extra steel reinforcement around the square opening shown in beams F-R and S-R showed an enhancement in the beam capacity compared with beams F-S and S-S which didn't have any strengthening with 8.23% and 31.42% respectively, which shows that both gave a good enhancement in the load capacity.

Strengthening the openings with a steel laminates was shown above in beam F-L-Steel and S- L-Steel, this strengthening technique showed an enhancement in beam F-L-Steel load capacity compared with Beam F-S which didn't have any strengthening with 8.23%. However, for beam S-L-Steel the enhancement was 21.42% which is considered low compared with the other strengthening techniques in shear zone. Also, it is confirming the previous conclusion that the effect of strengthening in the shear zone more effective than flexural zone.

Strengthening the beam with NSM rods in beams F-R-N and S-R-N, showed an enhancement in the beam load capacity, for flexure zone the beam load capacity increased by 11.76% showing the highest regaining in the load capacity compared with the other strengthening methods in flexure zone. Also for the shear zone beam S-R-N showed a significant enhancement in the load capacity with 35.7%.

Strengthening the beams with NSM laminates in beam F-L-N and S-L-N, showed an enhancement in the load capacity, for flexure zone the beam load capacity increased by 8.23% which is in average compared with the other techniques used in strengthening the openings in flexure zone. On the other hand, Beam S-L-N load capacity enhanced by 44.2% showing it's the highest load capacity compared with all the beams which have opening in shear zone.

6. Strain behavior

The strain behavior of beams was monitoring for all beams also for the strengthened beams, the strain behavior of the strengthening material was tracked as well, strain 1 points to the strain gauge attached to horizontal steel reinforcement and strain 2 points to the strain gauge attached to the strengthening material. The strain curves show that using FRP composites increased the stiffness of the beams which shows the effect of using FRP in strengthening the beams.

For the un-strengthened beams the strain curve show that the behavior of the beams didn't change, however the toughness of the beams with openings significantly decreased.

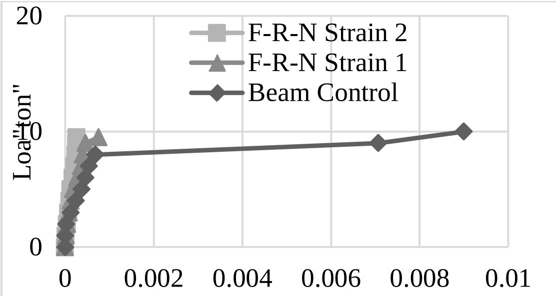

Figure 48: Strain curve for beam F-R-N

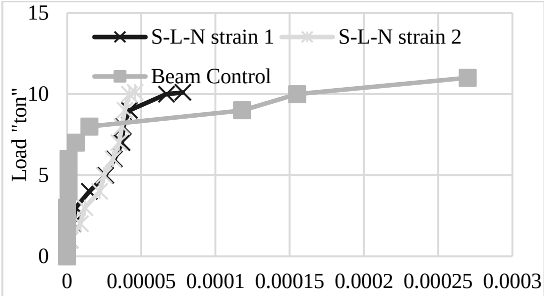

Figure 49: Strain curve for beam S-L-N

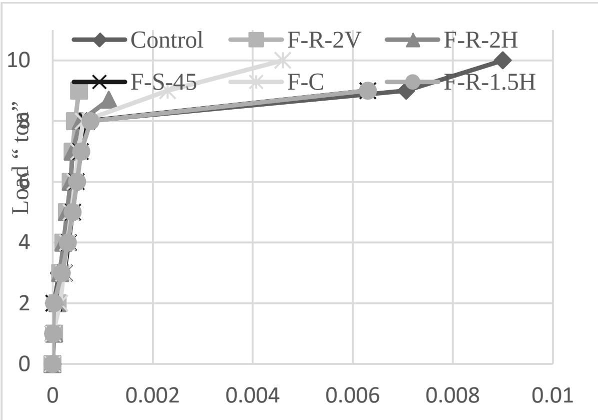

Figure 50: Strain curve for flexure zone unstrengthened beams

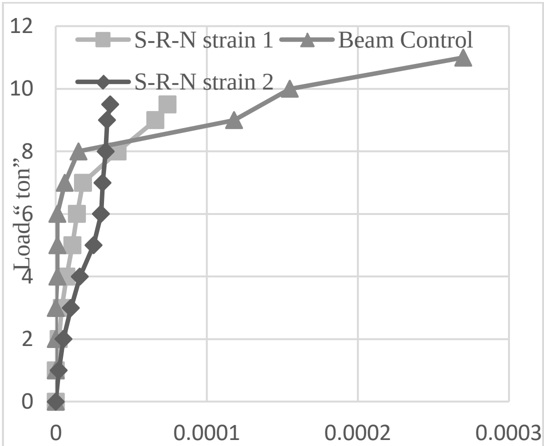

Figure 51: strain curve for beam S-R-N

7. Deflection ductility index

Using the load– deflection relationship it could be calculated the deflection ductility index. which based on deflection computation at mid-span of beam, the toughness of the beams was computed as an indication of ductility, Then a ratio between the ductility of beams to the ductility of control beam was computed, another ratio of the ductility of the strengthened beams to the ductility of each strengthened beam with the same opening zone and shape. Generally, a high ductility index indicates that a structural member is capable of undergoing large deformations prior to failure. The following table shows the efficiency of strengthening the openings in beam with different techniques on the term of ductility. [22] The data shows an improvement in the ductility of all strengthened beams compared with the beams without strengthening expect for beam F-R-N which had a brittle failure after the breaking of FRP rods. Also, the table shows that strengthening the beam internally with steel enhanced the ductility of the beam showing the same behavior as the control beam. For the beams strengthened externally with FRP laminates beam F-L-N shows a significant increase in the ductility of the beam compared with control beam. Also beam S-L-N showed the same ductility index as the control beam as well as beam F-L-

E. In terms of ductility strengthening the beam internally with steel reinforcement improved the ductility when compared to un-strengthened beams and shows the same ductility index as the control beam; also strengthening externally NSM laminates enhance the ductility of beams, also the data shows that the openings in flexure and shear zone significantly decreases the ductility of beams, however the circular openings showed an enhancement in the beam's ductility.

Table 3: ductility index table

Beam	Ductility	Ductility of beam / ductility of control beam	Ductility of beam / ductility of un-strengthened beam
Control	106.87	1	-
F-S	80.175	0.75	-
S-S	68.525	0.64	-
F-R	105.315	0.99	1.31
S-R	109.209	1.02	1.59
F-L-Steel	62.88	0.59	0.78
S-L-Steel	120.34	1.13	1.76
F-R-N	58.242	0.54	0.73
S-R-N	90.24	0.84	1.32
F-L-N	142.54	1.33	1.78
S-L-N	108.23	1.01	1.58
F-L-E	103.17	0.97	1.29
S-L-E	83.1	0.78	1.21
S-R-IER	51.52	0.48	0.75
F-R-1.5H	74.84	0.70	N.A.
F-R-2V	102.108	0.96	N.A.
F-R-2H	94.136	0.88	N.A.
F-S-45	85.395	0.80	N.A.
F-C	160.08	1.50	N.A.
S-R-1.5H	71.12	0.67	N.A.
S-R-2V	52.615	0.49	N.A.
S-R-2H	76.05	0.71	N.A.
S-S-45	89.32	0.84	N.A.
S-C	108.97	1.02	N.A.

8. Conclusion

This research provides information about the behavior on the strengthened beams with openings in shear and flexure zones with different techniques. Experimental results show the effectiveness of each strengthening technique, based on the results discussed in the paper, the following main conclusion can be drawn:

- Generally creating an opening in the beam greatly decreased the load capacity of the beam specially when the opening in the shear zone rather than flexural zone, so it is recommended to execute the open in the flexural zone when it is urgent to make open.
- Changing the orientation of square opening either 90o or 45o "Rhombus" did not make any significant

change either in shear and flexural zone; moreover, it is recommended to make the rectangular opening in vertical position rather than horizontal.

- The circular opening showed the highest performance compared with the other opening shapes in both shear and flexure zones followed by the horizontal rectangular opening with aspect ratio 1.5 and the lowest performance was the square openings
- In spite of the reduction in load capacity due to opening in shear zone much higher than flexural zone, the effect of strengthening in the shear zone more effective than flexural zone.
- Circular opening is the best shape of opening that showed the least reduction in ultimate load.
- The aspect ratio and orientation of the opening can affect the load capacity of the beam.
- When using the same area of laminates and rods in strengthening the opening in flexure and shear zones, the laminates sustain a better result with higher load capacity in shear zone however in flexure zone the FRP rods showed a better result.
- Using a steel box in strengthening the opening in flexure zone is feasible however it’s not effective in the shear zone, as the shear force tend to break the welding bonding between the steel plates.
- Using externally bonded laminates in flexure and shear was as good as N.S.M. rods in terms of load but in terms of deflection beams with E.B. laminates had higher defection.
- IER technique is not feasible in strengthening the opening in shear zone
- Further researches are needed to study the effect of IER method and the effect of the parameter like adding epoxy inside the grooves or changing the amount of reinforcement stirrups used as well as the spacing between the IER.
- Strengthening the beam internally with steel reinforcement improves the ductility of the beam to show the same limit of control beam.
- Enhancing the ductility of the beams with opening using FRP composites is feasible.
- Strengthening the opening in beam with NSM mounted technique in flexure zone can improve the ductility of beam to 33% compared with the control beam and 78% compared with the un-strengthened beam with opening in the same zone.

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